Feasibility of Dynamic Stability Measurements of Planetary Entry Capsules Using MSBS

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ABSTRACT

The feasibility of conducting dynamic stability testing of planetary entry capsules at low supersonic Mach numbers using a Magnetic Suspension and Balance System (MSBS) is reviewed. The proposed approach would employ a spherical magnetic core, exert control in three degrees-of-freedom (i.e. x, y, z translations) and allow the model to freely rotate in pitch, yaw, and roll. A proof-of-concept system using an existing MSBS electromagnet array in a subsonic wind tunnel is described, with future potential for development of a new system for a supersonic wind tunnel.

1. Introduction

Contemporary planetary entry capsules are characterized by a low length-to-diameter ratio, as illustrated in Figure 1. The dynamic stability of these shapes is critically important in the supersonic regime, prior to parachute deployment. Experimental testing at low supersonic Mach numbers has relied on aeroballistic ranges [1], but this approach can yield restricted quantity and quality of data. It may now be possible to develop an improved test facility for a conventional wind tunnel, based on use of an MSBS.

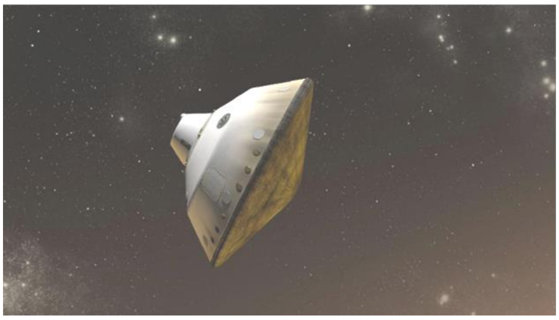

Fig.1 Mars Science Laboratory Capsule

One of the promises of Magnetic Suspension and Balance Systems for wind tunnel testing has been the possibility of dynamic stability testing using forced-oscillation or free-oscillation techniques [2]. Due to the geometry of typical planetary entry capsules, the free-oscillation technique is being explored, following an approach demonstrated in the 1970's at Princeton [3], the University of Virginia [4] and elsewhere. Here, a freely magnetized spherical iron core is placed inside a non-magnetic aerodynamic shell, such that magnetic torques cannot be generated, according to Equation 1.

$$\vec{T} = \oiiint \vec{M} \times \vec{B}\ dV \qquad (1)$$

Since $\vec{M}$ naturally aligns with $\vec{B}$ where the magnetic core exhibits a high degree of symmetry, magnetic torques are zero.

2. Analysis – Supersonic Facility

The aerodynamic drag force is assumed to be dominant in this application. The approximate dynamic pressure in a simple blowdown supersonic wind tunnel operating from an ambient temperature reservoir is presented in Figure 2. It is seen that modulating the stagnation pressure at low supersonic Mach numbers is advantageous. Assuming that this is done, a dynamic pressure of 60 kPa is a reasonable design target. Further reductions in dynamic pressure are possible, with improved pressure recovery and/or reductions in downstream exhaust pressures.

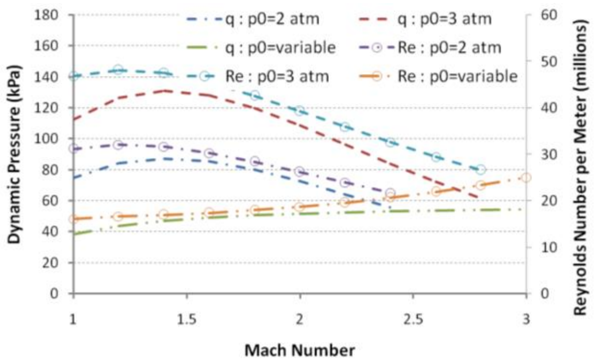

Fig.2 Dynamic pressure and Reynolds number per meter in a supersonic wind tunnel. 288K stagnation temperature; normal shock recovery; M=0.2 exhaust to atmosphere.

The magnetic force on a freely magnetized sphere and the consequent magnetic field requirements for overcoming the drag force are approximated by the following equations.

$$F_{mag} \approx M_x B_{xx}\, Vol \qquad (2)$$

$$F_{drag} = 0.5\, \rho\, V^2 A\, C_D = q\, AC_D \qquad (3)$$

$$B_{xx} \approx (3\, q\, C_D)/(2\, k^3\, D\, M_x) \qquad (4)$$

$$F_{mag}/m = (3\, q\, C_D)/(2\, k^3\, D\, \rho) \qquad (5)$$

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The parameter k is the ratio of magnetic core diameter to model base diameter. Assuming that the drag coefficient is 1.5 or so [5], that the value of k can be around 0.6, and that the magnetization of the iron core is driven to 2T (i.e. close to saturation), the required force per unit mass and axial field gradient are found to be:

Table.1 Required axial field gradient and magnetic force per unit core mass (q = 60 kPa)

D (cm)	2	4	6
B_{xx} (T/m)	19.6	9.8	6.5
F/m (N/kg)	3970	1985	1323

These are challenging values, but can be achieved, as will be illustrated later. A question arises as to the absolute maximum force that can be created on a spherical core. Computations of the magnetic force created on a sphere by a Helmholtz-like electromagnet pair carrying unequal currents, using COMSOL™ and illustrated in Figure 3, suggest no clear upper limit, although nonlinear (saturation) effects are apparent.

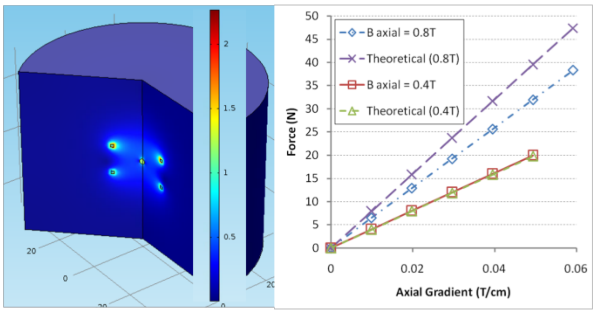

Fig.3 Calculations of Magnetic Force on a 2 cm Sphere

3. Proposed Proof-of-Concept System

In the mid- to late-1960's a team at MIT designed and developed a sophisticated MSBS that was used in both low-speed and supersonic wind tunnels [6]. The MSBS and low-speed wind tunnel were relocated to NASA Langley Research Center in the early 1980's and operated for a decade or so [7]. The electromagnet assembly (illustrated in Figure 4), the electromagnetic position sensing system (EPS), and the low-speed wind tunnel (illustrated in Figure 5) still exist and will form the basis of a subsonic proof-of-concept system. The electromagnets are water-cooled copper, with iron yokes for the lateral gradient coils. The design inherently provides some separation of magnetic field and gradient components between coils. The EPS position sensing system is rather unique, essentially operating as a multi-axis LVDT [6].

The wind tunnel can reach Mach 0.5 in the 15 cm test section, yielding a dynamic pressure of around 17.5 kPa. The design maximum axial magnetizing field was around 0.5 T and the design maximum axial gradient was nearly 4 T/m [6]. This yields a force per unit core mass capability of around 600 N/kg, approximately matching the requirement for a 4 cm base diameter model. These values suggest that dynamic stability testing can be demonstrated with this system at reasonably high dynamic pressures.

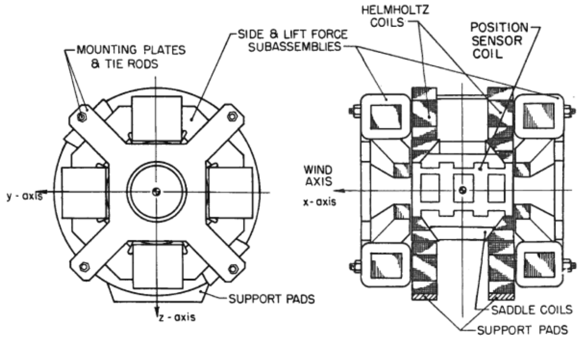

Fig.4 6-inch MSBS Electromagnet Assembly [6]

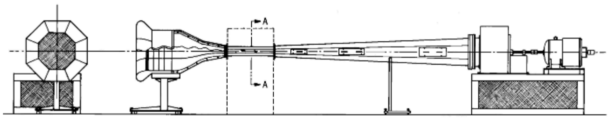

Fig.5 6-inch MSBS Low-Speed Wind Tunnel

Control of the magnetically suspended model will also be challenging, with very short time constants due to the high force per unit mass ratios. By way of example, the frequency of pitch oscillations in ballistic range testing can be of the order of 50 Hz with a 6.5 cm model at Mach 3.5 [1]. In this application the models are likely to be smaller and lighter, but operating at lower dynamic pressure, leading to similar frequencies in pitch. If translational control can be made stiff, then the system will approximate a mechanical free-oscillation rig. Lower stiffness will lead to more complex dynamics. An additional advantage of the MSBS approach might be the possibility of testing lifting configurations.

4. Concluding Remarks

Dynamic stability testing of planetary entry shapes at low supersonic Mach numbers using an MSBS appears to be a practical option. A proof-of-concept system can be constructed using an existing electromagnet array.

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